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The cloud chamber and CTR Wilson's legacy to atmospheric science

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Introduction and early life

2011 is the centenary year of the short paper (Wilson, 1911) first describing the cloud chamber, the device for visualising high-energy charged particles which earned the Scottish physicist Charles Thomas Rees ('CTR') Wilson the 1927 Nobel Prize for physics. His many achievements in atmospheric science, some of which have current relevance, are briefly reviewed here. CTR Wilson's lifetime of scientific research work was principally in atmospheric electricity at the Cavendish Laboratory, Cambridge; he was Reader in Electrical Meteorology from 1918 and Jacksonian Professor from 1925 to 1935. However, he is immortalised in physics for his invention of the cloud chamber, because of its great significance as an early visualisation tool for particles such as cosmic rays[1] (Galison, 1997). Sir Lawrence Bragg summarised its importance:

The cloud chamber has become the vital means for studying the ultimate particles of matter, and is responsible for a major part of modern physics. (Bragg, 1968)… *It can tell us the history of a single one of these minute particles, which leaves a trail in the cloud chamber like that left in the upper air by an aeroplane under certain meteorological conditions.* (Bragg, 1969)

Wilson was born at Crosshouse farm, Glencorse, on 14 February 1869. The family moved to Manchester where he enrolled, with his brother, to study medicine at Owens College; the brothers frequently returned to Scotland where they pursued the then popular scientific hobby of photography, for example producing images of clouds in the mountains. Following his Manchester degree Wilson obtained an entrance scholarship to Sidney Sussex College, Cambridge University,[2] in October 1888 (Figure 1). He intended chiefly to study physics, wary of limited employment prospects from undertaking the Mathematical Tripos alone. Natural landscapes retained a powerful lure to him he described himself as…*strongly impressed with the beauty of the world* (Wilson, 1960),

Figure 1. CTR Wilson in 1889. (Plate 8 of Wilson (1960), reproduced with permission of the Royal Society.)

and after his Cambridge scholarship he acted as a volunteer at Ben Nevis Observatory for a fortnight in September 1894. The Observatory was frequently shrouded in cloud and mist and the optical phenomena of coronas and glories he witnessed provided strong motivation for his experiments in imitating cloud processes in the laboratory (Wilson, 1927). He died in Edinburgh on 15 November 1959.

[1]Despite Wilson's awareness of background ionisation, cosmic rays themselves (i.e. high-energy particles from space) were discovered by Victor Hess (1883–1964) in balloon flights during 1911–1912; he was rewarded by the 1936 Nobel Prize for Physics.

[2]The Sidney Sussex student club for Natural Science is called the Wilson Society.

RMetS Royal Meteorological Society

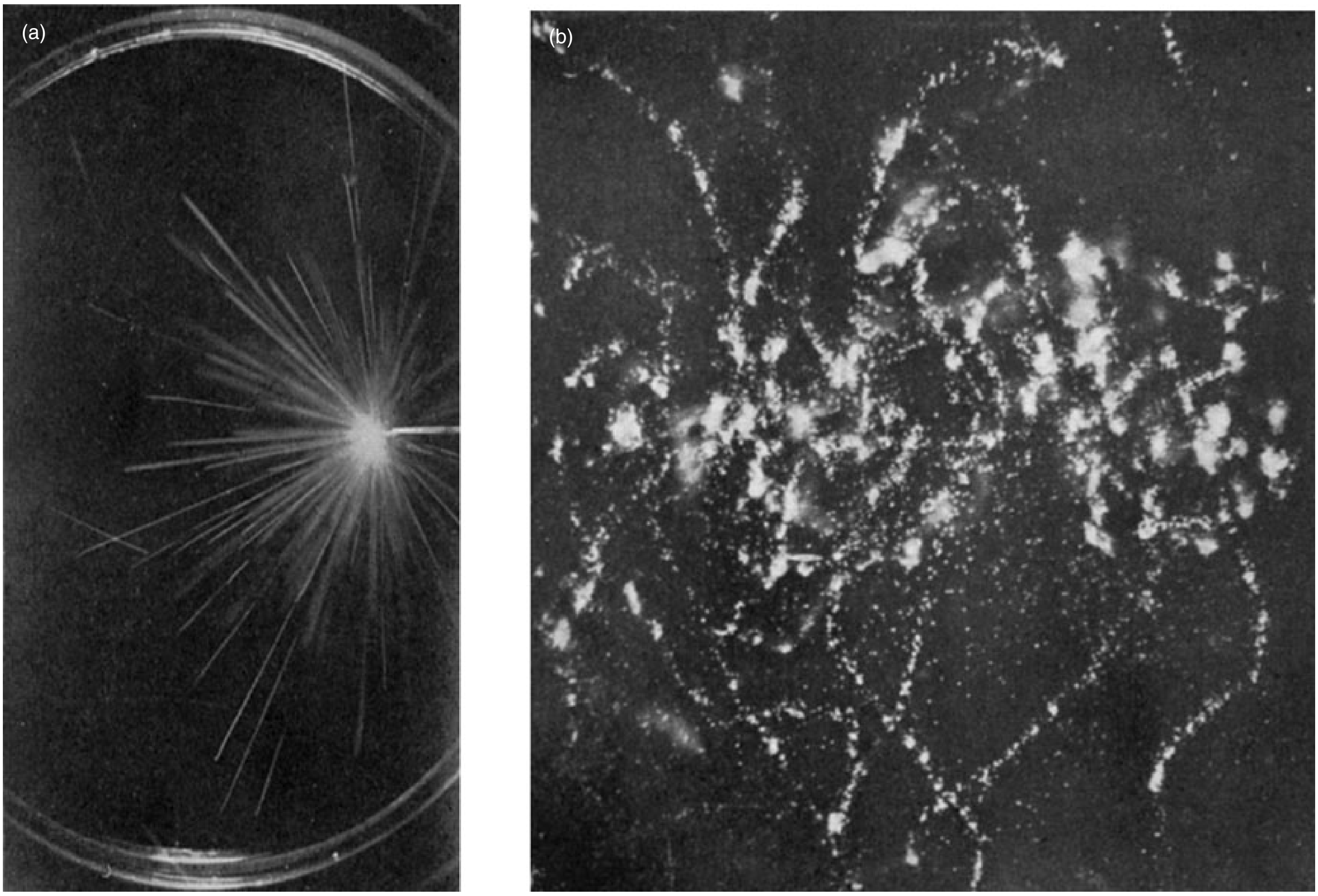

Figure 2. Cloud chamber images of (a) ionisation generated by a cylindrical X-ray beam about 2mm in diameter, passing right to left and (b) magnified tracks of ions formed by X-rays. (From Plates 8 and 9 of Wilson (1912), reproduced with permission of the Royal Society.)

Development of the cloud chamber

Wilson's Nobel Lecture acknowledged the influence on his experiments of the particle visualisation technology of the time, the condensation particle counter invented by John Aitken.[3] The operating principle of the Aitken counter was to moisten a sample of atmospheric air and then cool it by rapid expansion. The resulting substantial supersaturation of the air sample yielded droplet condensation on whatever particles (nuclei) were present, and these could be counted optically. Aitken made dust measurements at Ben Nevis Observatory (Aitken, 1889) between 1891 and 1894 on this basis, immediately prior to Wilson's visit. Wilson developed Aitken's expansion chamber technique to use filtered air. In a lecture broadcast two days after his 90th birthday Wilson described this approach:

> *I found that when all the dust particles, as Aitken called them, or what we should now call Aitken nuclei, had been removed, one still was able to produce condensation in the form of drops provided a certain quite definite degree of supersaturation was exceeded.* (Dee and Wormell, 1963)

Wilson had discovered that air always contained nuclei on which droplets could form if the water supersaturation was sufficient. His interpretation of these nuclei as charged particles (ions) was influenced by the then developing understanding of charged particles. Initially, he tried applying ultraviolet light to generate ions but, further inspired by an early demonstration of X-ray apparatus made for J. J. Thomson[4] at the Cavendish Laboratory, Cambridge, in 1896, he was delighted to find that X-rays greatly increased the number of droplets formed under the necessary high supersaturation. The fact that the droplets formed responded to an electric field demonstrated that the condensation nuclei were charged, i.e. that they were ions (Wilson, 1899). Figure 2 shows images of high energy particles made visible within a cloud chamber (Wilson, 1912). As the modern era is dominated by digital image production, the photographic effort once required to obtain such iconic scientific images may not be widely appreciated. For the strikingly beautiful pictures in Figure 2,

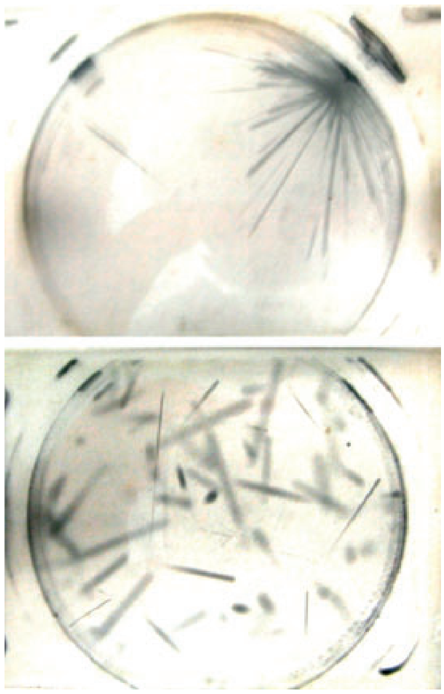

Figure 3. Cloud chamber images on the glass photographic plates employed.

[3] John Aitken (1839–1919) was a Scottish atmospheric physicist. He made detailed investigations into the properties of the Stevenson screen and, using his condensation instrument to detect atmospheric aerosol, he was the first to observe the formation of new atmospheric particles by nucleation.

[4] Sir Joseph John (J.J) Thomson was Cavendish Professor of Physics and a president of the Royal Society. He received the 1906 Nobel Prize in Physics for discovering the electron and research on the electrical conductivity of gases.

RMetS
Royal Meteorological Society

a stable photographic emulsion, the correct exposure, accurate focus and successful chemical processing yielding good contrast would all have been needed, quite apart from the opportune visualisation of a high-energy event. Figure 3 shows the glass negative plates which formed the basic photographic technology employed; the exposure dates are unfortunately unknown.

Furthermore, experimental scientists of Wilson's time almost always had to make their own apparatus, and Wilson was no exception, for example developing glass-blowing skills. As the Cavendish was relatively near London there may well have been technical exchange visits typical of the era (Gay, 2008) to see the latest creations, but of course international attention also followed publications describing the results. Wilson's work became widely known; he demonstrated the expansion apparatus to Stokes[5] and Kelvin[6] in the late 1890s, was elected a Fellow of the Royal Society in 1900 and, in 1903, met the Curies[7] during a Paris visit to see Langevin.[8]

Atmospheric electricity instrumentation

In 1900 the Meteorological Council sought Wilson's involvement for work on atmospheric electricity, which added to the existing demands of his expansion chamber work and a Fellowship at Sidney Sussex. Atmospheric electric field measurements had been made at Kew Observatory[9] since the 1840s by the flame probe and mechanical electrometer system, refined in the 1860s to utilise the photographic recording methods of Kelvin employing the water-dropper potential sensor (Harrison, 2003). The water dropper (or 'Kelvin electrograph') measured relative changes in the electric field,[10] but Wilson was to improve these techniques, largely through work undertaken during University vacation at the family home in Peebles, where his brother had a medical practice. Wilson's notebooks (Dee and Wormell, 1963) show his interest in atmospheric electricity from 1898, and his appreciation of new findings about air ionisation generated by radioactivity and X-rays no doubt further underpinned his atmospheric electricity instrumentation developments. He described (Wilson, 1906) apparatus which not only measured the potential gradient in a calibrated way, but, by observing the rate of change of an alternately exposed and covered electrode, determined the vertical current flow in fair weather.[11] Wilson's delight at obtaining measurements of the vertical current flow remained with him all his life, illustrating the importance that he attached to experimental observations:

> *I remember the satisfaction I had when my work led to the fulfilment of my dream of isolating a portion of the earth's surface and measuring the charge upon it and the current flowing into it from the atmosphere.* (Wilson, 1960)

The 'Wilson apparatus', as the Meteorological Office subsequently referred to it, demonstrated his immense experimental ingenuity and resourcefulness, for example in devising a guarding technique to minimise leakage current. He even deployed his childhood microscope for thunderstorm electricity measurements (Wilson, 1960). Evidence of the success of the Wilson apparatus lies in its longevity, as it was used in an almost identical manner until 1979 at Kew Observatory, having been moved to an underground laboratory in 1931 (Harrison and Ingram, 2005). Beyond its original scientific application, data from the Wilson apparatus has proved suitable for reconstructing historic air pollution data (Harrison, 2006).

Lifetime research themes

Familiarity with the current flowing vertically in the atmosphere in fair weather proved central to Wilson's later unifying ideas in atmospheric electricity. The Wilson apparatus' combination of potential gradient and conduction current measurements allowed simple calculation of the electrical conductivity of air from Ohm's Law. Air's electrical conductivity is almost exclusively due to the ions it contains. Hence Wilson could uniquely measure the concentration of atmospheric ions with his atmospheric electricity instrumentation, and visualise them by his expansion technique. He continued improving the expansion technique and in 1911 he published the short but pivotal paper summarising the application of the cloud chamber.

Wilson's notebooks (Dee and Wormell, 1963) show continued refinements of the cloud chamber beyond 1911 with improved photographs of ion condensation tracks, interleaved with atmospheric electricity research on, for example, thunderstorm electrification, droplet charging and development of a capillary electrometer. He used a small hut on the west side of Cambridge, now within the site of the New Cavendish laboratory, for his atmospheric measurements. One aspect of his work on disturbed weather atmospheric electricity is the extended discussion with G. C. Simpson[12] on the vertical charge structure of thunderstorms (Williams, 2009).

The global circuit concept

The origin of the potential gradient consistently present in fair weather atmospheric conditions has always remained a particular challenge to atmospheric science. Wilson argued that the conducting ionosphere provided the connection between electrified storms and the extensive fair-weather regions elsewhere (Wilson, 1921). The presence of an upper-atmospheric conducting layer had been postulated more than 50 years earlier (e.g. Chalmers, 1961), but was only firmly established experimentally by early radio studies. Wilson elaborated further on this idea, for which fundamental support was found through comparison of the potential gradient measurements made during global survey cruises by the research ship *Carnegie* with meteorological information on the global distribution of thunderstorms (Wilson, 1929; Whipple and Scrase, 1936). A close relationship was implied as both potential gradient and global thunderstorm area showed a maximum at 1900 UTC and minimum around 0400 UTC, no matter where the *Carnegie* was located at the time of the measurements.

Wilson's global atmospheric electrical circuit concept (Figure 4) argues that charge separated by shower clouds and thunderstorms is transferred through the ionosphere to fair weather regions. Fair weather vertical ion flow between the ionosphere and the surface, which Wilson so effectively observed, is directly linked to the surface potential gradient. Subsequent findings

[5] Sir George Stokes (1819–1903) was Lucasian Professor of Mathematics at Cambridge and a president of the Royal Society.

[6] Lord Kelvin (William Thomson, 1824–1907) was a President of the Royal Society, and made seminal contributions in thermodynamics and electrical engineering. He developed methods for continuous electric field recordings, concluding that the sensitivity of atmospheric electrical changes might prove useful in weather forecasting.

[7] Marie Curie (1867–1934) and Pierre Curie (1859–1906) shared the 1903 Nobel Prize in Physics with Henri Becquerel for their work on radioactivity; Marie Curie won the 1911 Nobel Prize in Chemistry.

[8] Paul Langevin (1872–1946) is known for his work on piezoelectricity and relativity, but also studied air ions.

[9] Kew Observatory in Richmond, London, was the principal site for meteorological developments and observations, originally established as an astronomical observatory in 1769 by George III. It was closed in 1980, but meteorological measurements continue nearby at an automatic weather station in Kew Gardens.

[10] The vertical atmospheric electric field E_z is, by convention, usually recorded as the potential gradient F, where $F = -E_z$.

[11] Construction of a simplified modern version of the Wilson apparatus is described by Bennett and Harrison (2007) at http://arxiv.org/abs/physics/0701280.

[12] Sir George Simpson (1878–1965) was the meteorologist on Scott's ill-fated Antarctic Expedition, longest-serving director of the Met Office (1920–1938) and, in 1940, president of the Royal Meteorological Society. His atmospheric electricity work included direct balloon-soundings of thunderstorms using a specialised sensor (the *alti-electrograph*).

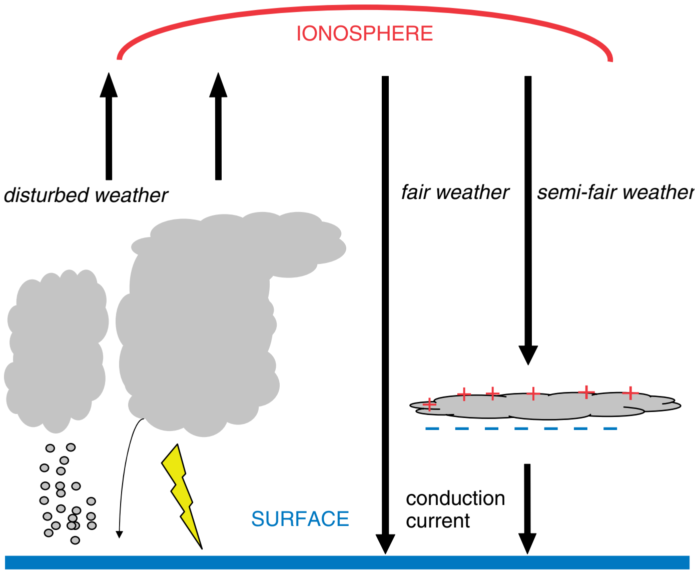

Figure 4. The global atmospheric electrical circuit. Charge separated in disturbed weather regions (thunderstorms and shower clouds) flows upwards to the conductive lower ionosphere and downwards to the surface (through lightning, precipitation and cloud discharge). The circuit is completed by a small vertical conduction current in distant fair weather regions and the Earth's surface. Where the vertical conduction current passes through semi-fair weather regions containing extensive layer clouds, charging is associated with the upper and lower horizontal cloud edges.

have extensively corroborated the concept of the global circuit, making it a useful explanatory framework for a wide range of phenomena (Aplin *et al*., 2008), indicating a CTR legacy far beyond the use of the cloud chamber in contemporary research. Indeed, the current flowing in the global circuit is referred to in modern literature as the Wilson current (Mach *et al*., 2011).

Legacy

Motivated by his early intentions to imitate nature, Wilson originally sought to link the behaviour of ions with atmospheric cloud formation (Galison, 1997). Despite the immense applicability of the cloud chamber for visualisation, the mimetic approach itself proved ultimately unsuccessful as the cloud chamber conditions needed differed vastly from those in the lower atmosphere: natural cloud droplets therefore cannot form on cosmic ray ions as they do in the cloud chamber. Where there may yet be a closer link between fair weather clouds and ions is at the cloud-air boundaries of extensive stratiform clouds, where edge-charging is observed from the global circuit current flow (Nicoll and Harrison, 2010). Wilson's broad interpretation of natural phenomena, firmly rooted in laboratory and field experimentation, therefore remains inspirational in the understanding of fundamental atmospheric processes.

In summary, CTR Wilson's visualisation techniques for particle physics concerned microscopic cloud processes, whereas his synthesis of atmospheric electricity unravelled invisible atmospheric properties on a global scale. Half a century after his death, it is a tribute to his painstaking reasoning and wonderful experimental ingenuity that both his principal scientific achievements still influence physics education and atmospheric electricity research.

Acknowledgement

Andrew Wilson provided the glass plates from his grandfather's cloud chamber photographs shown in Figure 3. I am also grateful to Alan Watson, Michael Rycroft and Karen Aplin for their insights.

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